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WAVELENGTH AGILE LASER

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CROSS REFERENCE TO ATTACHED APPENDIX

Appendix A contains the following files in one CD-ROM (of which two identical copies are attached hereto), and is a part of the present disclosure and is incorporated by reference herein in its entirety:

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Volume Serial Number is B2B0-391B
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09/10/01  09:08a                     1,405 PFE_HELP.M
09/10/01  09:08a                     5,441 PFILT.M
                   5 File(s)        10,914 bytes
   Total File(s) Listed:      10,914 bytes
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BACKGROUND

The evolution of telecommunications networks has been such that the complexity and speed of networks in general have greatly increased. In addition to the development of network design, new and novel optical components are being brought to bear on the issues of speed and reach of optical channels. A particular aspect of network design is the need for dynamic configuration of networks. For example in an optical mesh many circuits based on an assignation of a specific wavelength are set up and reconfigured either for reasons of efficient traffic engineering or restoration. For a detailed description of optical network design see Journal of Lightwave Technology, Special Issue on Optical Networks, December 2000, vol. 18 pages 1606-2223 inclusive, the contents of which are incorporated by reference herein.

An enabling device for such next generation optical networks is a wavelength agile laser. A wavelength agile laser (hereafter "laser") is a lasing device that may be tuned to either any discrete wavelength or arbitrarily tunable (or continuously tunable) within a given wavelength window. For telecommunications applications involving dense wavelength division multiplexing (hereafter DWDM) the wavelength range used is in what is known as the third window. The third window is the spectral region within

which the attenuation exhibited by the transmission medium (commonly silica glass) is the lowest. Although loosely defined the third window may be identified to lie in the spectral region from 1500 nm to 1650 nm. Within this window the designations "S", "C" and "L" represent subdivisions of this spectral region.

A requirement of tunable laser performance is therefore the capability to address the spectral region associated with S, C and L-band wavelengths. A further requirement of a tunable laser is that it is compliant with what is known as the "ITU grid". The ITU grid is a defined standard covering the placement, in frequency space, of optical channels launched onto a fibre. In addition to the wavelength tunability requirements wavelength agile lasers must exhibit optical specifications compatible with high performance optical transmission. For a detailed description of the structure an optical performance requirements set on transmission lasers see J. Gowar, "Optical Communications Systems", Second Edition, Prentice Hall International Series in Optoelectronics, pages 257 to 487, inclusive, the contents of which are incorporated herein as background.

An additional application enabled by tunable lasers is that of hardware restoration of an optical link in the event of the failure of a transmission source(s). A logical link may be assigned a specific wavelength from amongst a stream of optical wavelengths and, in order to protect every link, every wavelength must be protected individually. This leads therefore to the need for 100% redundancy in an optical transmission system and a consequent doubling of the equipment cost. The reason for this duplication in

equipment is the very limited tunability of existing laser transmission sources. For a detailed description of the semiconductor based solutions to tunable laser solutions see V. Jayaraman et al., "Theory, Design and Performance of Extended Range Semiconductor Lasers with Sampled Gratings", IEEE Journal of Quantum Electronics, vol. 29, no. 6, June 1993 the contents of which are incorporated herein as background. In addition see Session TuL from Optical Fibre Communications 2000, (OFC 2000) Technical Digest p. 177 onwards the contents of which are incorporated herein.

One approach to an electro-optically controllable filter is the work of Alferness et al., as described in U.S. Patents 4,384,760, 4,390,236, 4,533,207, 4,667,331, 4,728,168, each of which is incorporated by reference herein in its entirety. A device of this type may also be seen in the article entitle "Narrow Linewidth, Electro-Optically Tuneable InGaAsP-Ti:$LiNbO^3$ Extended Cavity Laser" by F. Heisman et al., Applied Physics Letters, 51, page 64 (1987), which is incorporated by reference herein in its entirety.

Wavelength selected polarization mode coupling is described in U.S. 5,499,256 issued to Bischel et al., which is also incorporated by reference herein in its entirety. Electrode structures disclosed in the above-described patents are similar to the ones disclosed by the Kaminow in U.S. Patent 3,877,782 that is also incorporated by reference herein in its entirety.

SUMMARY

In accordance with the invention, an electric field that changes across a distance in space is synthesized, by

applying at several locations voltage levels that are independent of one another. The independence in voltage levels that can be applied is in contrast to U.S. Patent 3,877,782 that discloses application of a single voltage level to adjacent locations (see FIG. 2 of U.S. Patent 3,877,782), and alternatively a single voltage level to successive but non-adjacent locations (see FIG. 1 of U.S. Patent 3,877,782).

Specifically, in one embodiment of the invention, two or more voltage levels are applied at a number of locations successively one after another along a predetermined direction, thereby to synthesize an electric field that changes along the predetermined direction. Application of voltage levels independent of one another at non-adjacent locations allows an electric field that is synthesized to be made periodic or aperiodic. Moreover, such a synthesized electric field may be changed at any time for use in, for example, a tunable laser.

In one embodiment, the voltage levels are oversampled, although in other embodiments the voltage levels need not be oversampled, e.g. if the to-be-synthesized electric field is aperiodic. Furthermore, in one embodiment, the electric field is used to change the refractive index of an electro-optic substance (such as lithium niobate) in an optical filter, although in an alternative embodiment no electro-optic substance is used with the electric field, to form a multi-mode laser.

An optical filter formed by synthesis of an electric field as described above can be used in any telecommunication device, such as an optical add drop multiplexer or an optical switch. Such a filter can also be

used for dynamic power balancing and/or for dynamic gain equalization.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A illustrates, in a perspective view, a number of electrode E1-EN, to which are applied a number of independently controllable voltage levels V1-VN in one embodiment of the invention.

FIG. 1B illustrates, in a high level flow chart, acts performed in a method using the electrodes of FIG. 1A.

FIG. 2A and 2C illustrate, in perspective views, two implementations of electrodes of FIG. 1A to which are applied a number of voltage levels that change in space as a function of distance.

FIG. 2B illustrates, in a flow chart, one implementation of the method illustrated in FIG. 1B.

FIGs. 3, 7, 10, and 20A illustrate, in graphs, sets of voltage levels to be applied to the electrodes of FIG. 1A.

FIGs. 6A and 6B illustrate, in graphs, voltage levels applied to and electric fields generated by use of an electrode structure of the prior art.

FIGs. 4, 8, 11, and 20B illustrate, in a contour plot, the electric field generated by application of the voltage levels of the respective FIGs. 3, 7, 10, and 20A as a function of distance along the predetermined direction P in which electrodes E1-EN of FIG. 1A are arranged.

FIGs. 5, 9, 12 and 20C illustrate, in a graph, the voltage gradient at fixed distances in the vertical direction directly underneath the electrodes E1-EN of FIG. 1A.

FIG. 13A illustrates, in a perspective view, an electrode structure in which adjacent electrodes are offset from one another in a direction perpendicular to the direction P along which the electrodes are positioned successively one after another.

FIG. 13B illustrates, in a perspective view, electrodes of a number of different shapes that may be used depending on the embodiment,

FIG. 14 illustrates, in a perspective view, an electrode structure having two sets of electrodes to which may be applied two sets of independently controllable voltages V1-VP and W1-WP.

FIG. 15 illustrates, in a perspective view, another electrode structure that includes one set of electrode to which may be applied a corresponding set of independently controllable voltages V1-VN, and another electrode having a number of portions (also called "fingers") corresponding to the just-described set of electrodes.

FIGs. 16-19 and 21 illustrate, in perspective views, use of an electrode structure of the type illustrated in FIG. 1A, with wave guides of different configurations that may be formed in, for example, an electro-optic substance for use in telecommunication applications.

FIGs. 20D and 20E illustrate respectively, in an enlarged view, graphs of FIGs. 20B and 20C.

FIG. 22 illustrates, in a cross-sectional view, a block diagram using the arrangement of FIG. 16 to form a wavelength agile laser.

FIG. 23 illustrates, in a high level block diagram, circuitry for use in the laser of FIG. 22.

FIG. 24 illustrates, in a flow chart, software for use in the computer of FIG. 23.

FIG. 25 illustrates, in a cross-sectional view, similar to the view of FIG. 22, and optical further formed using the arrangement of FIG. 16.

FIGs. 26-29 illustrate, in high level block diagrams, alternative circuits for use in the laser of FIG. 22.

DETAILED DESCRIPTION

In accordance with the invention, an electric field that changes across space is synthesized, by applying two or more voltage levels that are controllable independently of one another. In one embodiment illustrated in FIG. 1A, several voltage levels V1-VN are applied to a number of electrodes E1-EN (wherein $1 \leq I \leq N$, N being the total number of electrodes) that (a) are insulated from one another, and (b) are positioned successively one after another along a predetermined direction P.

In FIG. 1A, a common set of index numbers I-N are used, for voltage levels V1-VN as well as for electrodes E1-EN, to indicate that each electrode EI can be at a different voltage level than every other electrode EJ. Depending on the implementation, voltage levels V1-VN may have either a

coarse resolution (e.g. in the limit just two values V1 and V2) or a very fine resolution (e.g. 200 levels, separated by 0.1 volt between adjacent levels).

Application of such voltage levels synthesizes an electric field (not shown in FIG. 1A) that envelopes electrodes E1-EN. The electric field changes in a predetermined manner (defined by voltage levels V1-VN) along the predetermined direction P.

Voltage levels V1-VN may be determined (see act 102 in FIG. 1B) from a mathematical model of a to-be-synthesized electric field that may be selected (see act 101 in FIG. 1B) by a designer of a device in which the electric field is used. The designer may select a mathematical model of the electric field, based on a number of factors, such as the physical principles involved in using the electric field. Examples include coupling between (a) two forward propagation modes of light and (b) a forward propagation mode and a backward propagation mode.

In one embodiment, each voltage level VI is determined (based on a preselected mathematical model of the to-be-generated electric field) in act 102 to be any value in a predetermined range, e.g. 0-20 volts. For this reason, each voltage level VI (FIG. 1A) is controllable independent of all other voltage levels to V1-VI-1 and VI+1 to VN. Such independence is in contrast to U.S. Patent 3,877,782. The independence in application of voltage levels to electrodes of an array of the type described herein eliminates the need to change the spatial distance between electrodes of the type described in U.S. Patent 3,877,782 to synthesize electric fields of different periods or even aperiodic electric fields.

In other embodiments, voltage level VI may be constrained, for example, to be same as another voltage level at another electrode as long as it is independent of at least (a) the adjacent voltage levels VI+1 and VI-1 that one applied at preceding and following electrodes EI+1 and EI-1 and (b) the successive but non-adjacent voltage levels VI+2 and VI-2. The respective electrodes EI+2 and EI-2 are successive but non-adjacent to electrode EI because there is an intervening electrode, namely electrode EI+1 or EI-1 respectively. For this reason, usage of voltage levels in such other embodiments is also different from usage on the voltage levels described in U.S. Patent 3,877,782.

Independent control of voltage levels applied at successive adjacent and non-adjacent electrodes allows the electric field that is synthesized (by application of these voltages) to be made periodic or aperiodic in space, depending on the values of VI-2, VI-1, VI, VI+1, and VI+2. Such a synthesized electric field may be changed at any time, simply by changing the voltage levels being applied.

Therefore, an electric field that is synthesized as described above can be re-synthesized at any time, for use in, for example, a tunable laser. Such re-synthesis of the electric field may be performed, for example, in response to a feed-back signal., indicative of an effect of the electric field, such as the power of a tunable laser at a specified wavelength, for use in, e.g., telecommunications.

In one embodiment, the voltage levels V1-VN (FIG. 1A) that are determined from a mathematical model as described above are oversampled, although in other embodiments the voltage levels V1-VN need not be oversampled, e.g. if the to-be-synthesized electric field is aperiodic. Oversampled

voltage levels represent values that are more in number N than a minimum number required to define the highest frequency component in the to-be-synthesized electric field (also called "desired" electric field).

If voltage levels are applied to electrodes E1-EN that are to be spaced apart from one another at a regular distance in the predetermined direction P, then a desired electric field with a highest frequency component of frequency f requires a minimum spatial electrode frequency of 2f, according to the Nyquist criterion. Therefore, in one embodiment, the spatial frequency of electrodes E1-EN is selected to be greater than 2f, so that the oversampling ratio is greater than 1.

The spatial frequency of the highest frequency component in an electric field, when used to generate Bragg reflection (as discussed below) may be, for example, 4 million/meter and when used for polarization mode conversion (also discussed below) may be, for example 1 million/meter. Such electric fields may be generated with a pattern having 100,000 electrodes/meter. The amount of oversampling that is needed (and therefore the electrode density) is chosen by a designer, based on the type of device to be built.

Oversampled voltage levels are obtained, in one implementation, from a mathematical representation (e.g. by use of a formula programmed into a personal computer) of a distribution in space of the desired electric field. In an example illustrated in FIG. 2A, the following formula represents the electric field to be synthesized:

$$VI = V*\cos [(I/2)* \pi] \tag{1}$$

wherein VI is the voltage level to be applied at electrode EI, +V to -V is the range of voltage levels that can be applied and I is an index number of the electrode EI, in a relative order of electrodes E1-EN along the predetermined direction P. As noted above, index number I starts at 1 and is successively incremented once per electrode until N is reached.

As seen from equation (1) above, the voltage levels V1-V4 to be applied to the first four electrodes E1-E4 are 0, +V, 0, and -V respectively. In this example, the number of electrodes per period is 4. In contrast, the Nyquist criterion for defining the same electric field requires only 2 electrodes per period in this example, so that the oversampling ratio is 2. The same electric field can be oversampled at any oversampling ratio F by using the following formula to generate voltage levels. $VI = V^* \cos([I/F]^*\pi)$

In the example illustrated in FIG. 2A, a mathematical model of an electric field selected by use of equation (1) (see act 111 in FIG. 2B) happens to be periodic in space, although such a model may be aperiodic in other embodiments. Therefore, an electric field that is synthesized by application of a sequence of independently controllable voltage levels may or may not be designed to be periodic in space, e.g. depending on the device in which the electric field is to be used.

Furthermore, regardless of the electric field being periodic or aperiodic, spacing of electrodes may also be periodic or aperiodic, depending on the implementation. If the spacing of electrodes is aperiodic, this aperiodicity is

used with the mathematical model to determine the appropriate voltage levels V1-VN.

Although in FIG. 2A, each electrode EI is illustrated as being at one of the three voltage levels 0, +V and -V, in an alternative embodiment only two such voltage levels may be used. For example, if the voltage levels +V and -V are used, a number of electrodes that are adjacent to one another may carry the same voltage level, e.g. electrodes EI-E3 (FIG. 1A) may carry the same voltage level +V, followed by the next three electrodes E4-E6 carrying the other voltage level -V, with this pattern repeated for all of the remaining electrodes.

Furthermore, depending on the specific electric field to be generated, the number of electrodes that are at the same voltage level may progressively increase or progressively decrease in the predetermined direction P. For example, the first six electrodes may define a waveform as just described (i.e. with the first three electrodes at voltage level +V and the next three electrodes at the voltage level -V), followed by eight electrodes that define a similar waveform that has a larger wavelength (i.e. for electrodes at voltage level +V followed by four electrodes at voltage level -V). In this example, the next ten electrodes define another similar waveform having a longer wavelength than the just-described first two sets of electrodes (of six electrodes and eight electrodes respectively).

An electric field synthesized by application of a pattern of voltage levels of the type described in the above examples has an instantaneous spatial frequency that decreases over distance in the predetermined direction P.

In one embodiment, such a field is used to implement a chirped grating (when the electric field is applied to a substance that exhibits a change in the refractive index in response to presence of the electric field).

An electric field having an instantaneous spatial frequency that increases or decreases over distance in the predetermined direction P can also be synthesized by use of voltage levels that have resolution more than two, e.g. having a resolution of 0.1 volt, and within a voltage range of 0-20 volts (which means that any voltage level VI can be set to one of 200 different values). Moreover, although FIG. 2C illustrates only one waveform for each of the instantaneous spatial frequencies, any number of such waveforms may have the same instantaneous spatial frequency.

Although in FIG. 2C two voltages +V and -V have been illustrated, other voltages can be used in other embodiments, e.g. +V and 0, where 0 represents the ground reference voltage. Furthermore, although the electrodes are illustrated in FIG. 2C as being spaced at a fixed distance between two adjacent electrodes, such a distance can be changed for example so that the electrodes are arranged at a progressively larger distance or smaller distance in the direction P.

Furthermore, in yet another embodiment, a waveform is periodic in frequency, i.e. the same waveform is repeated over and over, except that an amplitude of the waveform is progressively increased or progressively decreased, in the predetermined direction P. In one implementation of such an embodiment, the amplitude of the waveform is progressively increased as an index of the electrodes increases from one to N/2 and thereafter progressively decreased until the

index reaches N. Such an implementation is used in, for example, forming a hamming filter of the type described in section 7.4 entitled "Design of FIR Filters by Windowing" in book Discrete-Time Signal Processing" by Alan V. Oppenheim and Ronald W. Schafer that is incorporated by reference herein its entirety.

In one embodiment, the electrodes are spaced at a regular distance between two adjacent electrodes, and a mathematical model of a fixed maximum amplitude waveform that repeats over and over in the predetermined direction P as illustrated by the following equation is used to generate the voltage levels to be applied to the electrodes.

$$VI = 15*\mathrm{Sin}\ ([I-1]*\ \pi/5.25) \qquad (2)$$

As seen from the above equation (2), an oversampling factor of 5.25 is used, to yield a set of voltage levels illustrated in FIG. 3 having a period λe of 10.5 electrodes. If the period λe (FIG. 2A) is 10.5 electrodes (which have a 2 micron pitch), the voltage potential in the space enveloping the electrodes is illustrated in the contour plot of FIG. 4, wherein each contour plot represents 10% decrease in the voltage level. In the contour plot of FIG. 4, the horizontal axis represents the distance in direction P, and the vertical axis represents distance in direction Z (FIG. 2A). A slice S of the contour plot of FIG. 4 at the distance -1 micron (i.e. one micron below the electrodes) yields the graph illustrated in FIG. 5, having the vertical component of the electric field (i.e. $-\partial V/\partial x = Ex$) plotted along the vertical axis of FIG. 5.

The waveform illustrated in FIG. 5 better approximates a sinusoidal waveform than a corresponding prior art waveform illustrated in FIG. 6A (that is obtained by application of alternating voltages to successive electrodes) so that the oversampling rate is 1 as per the prior art. Specifically, the waveform of FIG. 5 has a constant slope at the electrodes (e.g. in the circle C1), as compared to the waveform of FIG. 6A that has a changing slope (e.g. as illustrated in circle C2). Moreover, as the voltage potential increases away from the electrodes in FIG. 5, there is an increase in the slope (e.g. as illustrated in circle 3C) in contract to an unchanging slope in the corresponding region of FIG. 6A. Furthermore, the electric field pattern obtained by use of the voltage levels of FIG. 6A is fixed as illustrated in FIG. 6B, whereas such a pattern may be changed in accordance with the invention.

The waveform of FIG. 5 is not sinusoidal at the extremities (e.g. as illustrated in circle C4), which represent near field effects, and which may or may not be used, by appropriate design of the distance of a waveguide from the electrodes (e.g. less than 2 micron distance in this example results in a change in refractive index of a waveguide due to near field effects). The near field effects of the waveform in FIG. 5 are no worse than the corresponding near field effects of the prior art waveform in FIG. 6A. For the just-discussed reasons, oversampled voltage levels are applied to the electrodes in one embodiment of the invention.

With appropriate applied voltage levels, it is possible to synthesize a wide variety of electric field patterns. For example, as illustrated in FIGs. 7-9, the spatial period

of the electric field patterns synthesized by the use of independently controllable voltages as described above can be changed. For example, an initial period of 21 microns can be increased to 2*11.37213455 microns simply by changing the voltage levels applied to the various electrodes. In this example, as illustrated in FIG. 7, the voltage level applied to electrode E6 has been increased to a little over 5 volts from the previously applied voltage level of around 2.5 volts, and the voltage level applied to electrode E7 has been also increased from a voltage level of approximately -6 volts to a voltage level of approximately -2.5 volts (compare FIGs. 3 and 7).

Application of the two sets of voltage levels (illustrated in FIGs. 3 and 7) to the same set of electrodes at different times allows a device that uses the electrical field to be made tunable, e.g. a wavelength agile laser or a tunable optical filter. Furthermore, the position of such an electric field relative to the device, e.g. by starting the application of the voltage levels after a certain number of electrodes that are simply left floating, or alternatively coupled to the ground reference voltage. For example, FIG. 10 illustrates that the first three electrodes are not used, thereby to shift the position of the electric field in the predetermined direction P by almost ¼ of a wavelength.

A salient point of the just described embodiments illustrated in FIGs. 3-5 and 7-12 is the ability to synthesize electric field patterns that allow the wavelength at which mode conversion occurs to be shifted as desired by purely electronic means, as described below in reference to FIGs. 21 and 22.

Although electrodes E1-EN are illustrated in FIGs. 1A and 2A as being in-line with one another, the electrodes can also be offset by a distance O in other embodiments. Specifically, as illustrated in FIG. 13A, an electrode structure 121 has a set of electrodes F1-F4 that are in-line with one another along line F, and another set of electrodes G1-G3 that are also in-line with one another along line G. Although only a total of seven electrodes, namely F1-F4 and G1-G3 are illustrated in FIG. 3A, any number of such electrodes may be present in electrode structure 121, along the respective lines F and G.

Moreover, although only two lines F and G are illustrated in FIG. 13A, any number of such lines may be used, depending on the implementation of the electrode structure. Furthermore, although in FIG. 13A, lines F and G are illustrated as being coplanar, in other embodiments of such electrode structures, the lines along which electrodes are arranged may be non-coplanar, e.g. arranged around a cylindrical surface, or around a conical surface with an access coinciding with the predetermined direction P.

Furthermore, although in FIG. 2A, the electrodes E1-EN are illustrated as having an elongated shape, i.e. of length L (FIG. 2A) << the width W, e.g. L is two orders of magnitude greater than W, electrodes of other shapes may also be used as illustrated in FIG. 13B. Specifically, an electrode structure of the type described herein may contain a circular electrode 122A, or a square electrode 122B, or a triangular electrode 122C. Moreover, an electrode structure may include an electrode that has two portions connected to one another by a conductive line wherein the conductive line has any orientation relative to a line that is connected to

a voltage supply, e.g. in line as illustrated by electrode 122D or lateral, as illustrated by electrode 122E.

Furthermore, shapes of such portions may not necessarily be square as illustrated in FIG. 13B, and instead could be any other shape as noted above. Similarly, an electrode 112F may have an elongated oval or elliptical shape. Therefore, it is to be understood that the specific shape of an electrode in the electrode structure 122 (FIG. 13B) is not critical to some embodiments, as long as an electric field is synthesized as described above.

In another embodiment, an electrode structure 125 (FIG.14) has a set of electrodes 123, with each electrode individually labeled 123A-123P, wherein P ≥ K ≥ A, and another set of electrodes 124 which are individually labeled 124A-124P. Each electrode 123K in set 123 is located along a line F, and a corresponding electrode 124K in set 124 is located along line G. The two corresponding electrodes 123K and 124K are offset from one another by a distance O between lines F and G, and are otherwise colinear, i.e. are located along a line K which is perpendicular to each of lines F and G.

In electrode structure 125, each electrode 123K is coupled to a source of a corresponding voltage VK which is independent of the voltage of any other electrode in set 123. Similarly, each electrode 124K in set 124 is coupled to a source of voltage WK that is independent of the voltage applied to any other electrode in set 124. The voltages VK and WK that are applied to the corresponding electrodes 123K and 124K respectively may have a predetermined relationship, e.g. VK = WK.

In an alternative embodiment illustrated in FIG. 15, a number of portions in electrode 124 do not carry a voltage level independent of one another, and instead are coupled to a source of the same voltage level, V0, for example, through a conductive strip 124C also included in electrode 124. The voltage level V0 may be, for example, the ground reference voltage. Note that in the electrode structure 126 illustrated in FIG. 15, the electrodes in set 123 may carry voltage levels independent of one another as described above.

For convenience, reference numeral 124 has been used to refer to a single electrode in FIG. 15, although the same reference number 124 illustrates a number of electrodes that carry voltages independent of one another in FIG. 14. To reiterate, each of portions 124A-124P in FIG. 15 are coupled to one another and carry the same voltage level V0. In many other respects, portions 124A-124P of electrode 124 are physically arranged in manner similar or identical to that described above for the individual electrodes 124A-124P in FIG. 14.

The electrode structures illustrated in Figs. 14 and 15 provide a horizontal electric field variation in the space between sets 123 and 124 whereas the electric field variations with the electrode structure of FIG.1A is vertical (Z direction).

An electrode structure of the type described above, wherein a number of electrodes are coupled to sources of voltage levels that are controlled independent of one another may be used to synthesize an electric field in any device that uses an electric field. Therefore, although certain embodiments of telecommunication devices that use

such a structure are described below, other kinds of devices can also be built using an electric field that is synthesized as described above.

In one embodiment, a device contains electro-optic material present in an electric field that is synthesized as described above, and in the presence of the electric field, the electro-optic material exhibits a change in refractive index. Depending on the implementation, the electro-optic may exhibit a refractive change that is proportional to the strength of the electric field. The independent control of the voltage levels applied to the electrodes in such a device to synthesize the electric field permits the electric field to be changed and therefore permits a change in the refractive index at any given location in the device. The electric field pattern to which the electro-optic material is exposed in the device is the sum of all of the independent contributions from each individual electrode in the electrode structure as discussed above.

In the presence of an electric field vector an electro-optic material exhibits a change in refractive index proportional to the field strength. Several of the embodiments described herein utilize the application of voltages of varying sign and varying magnitude to independently controllable electrodes. This technique not seen heretofore in the prior art. The electric field pattern to which the electro-optic material is exposed is therefore the sum of all the independent contributions from each individual electrode.

The generated electric field may be used to cause refractive index to change (either periodically or aperiodically) along the predetermined direction, which in

turn is used in devices that convert energy between multiple modes of light, e.g. from a forward propagation mode to a backward propagation mode, or between two or more forward propagation modes (such as polarized light from TM mode to TE mode). Examples of such devices include Bragg reflectors, polarization mode converters, and devices that use waveguides having same or different propagation constants and/or waveguides that have the same or different geometries (such as between a single mode waveguide and a multimode waveguide).

The positioning of the electrodes is such that the electric field distribution produced by application of voltage to the electrode array overlaps substantially with the guided optical mode. In one embodiment, an electrode structure 100 having a number of electrodes coupled to voltage sources that are independently controllable is located adjacent to a waveguide 132 (FIG. 16) that is formed inside an electro-optic material 131. Electro-optic material can be, for example, lithium niobate chip, or any other material that is electro-optic. A waveguide may be formed in material 131, e.g. by diffusion of titanium in the normal manner. Electrode structure 100 may be formed in contact with such a lithium niobate chip, for example, if loss of power of the light due to absorption by electrode structure 100 can be tolerated in an optical device of the type described herein.

Alternatively, if electrode structure 100 is formed of a metal, the waveguide 132 may be separated from electrode structure 100 by a buffered layer 134 (FIG. 21) that may be formed of any optically non-absorbing material, such as silica. Referring back to FIG. 16, electro-optic material

131 may have an anti-reflective layer 133 at an entry point of waveguide 132, so that most of the energy incident on waveguide 132 is transmitted therethrough.

At least a portion of the energy is reflected back, for example, due to satisfaction of the Bragg condition for reflection. Specifically, an electric field that is synthesized as described above in reference to FIG. 1A is used to cause periodic variations in the index of refraction of material 131, and the period of the index modulation is chosen to cause reflection of light off a particular wavelength, called the Bragg wavelength. Typically, the light at the Bragg wavelength is reflected back, while light of all other wavelengths is transmitted through waveguide 132.

By changing the voltage being applied at each of the electrodes of structure 100, the wavelength of light that is reflected back from waveguide 132 may be chosen, thereby to make the reflector tunable relative to the wavelength of light. Such a device may be used as an optical filter for adding and dropping single wavelength channels at node of a telecommunication network. When used in such telecommunication applications, the electric field that is synthesized by use of electrode 100 may be chosen to reduce the side lobes in spectral response of the optical filter to provide an improved spectral discrimination. The side lobe production can be obtained by varying the strength of the electric field in the predetermined direction P.

Furthermore, the electric field that is impressed on a waveguide 132 of the type illustrated in FIG. 16 may be aperiodic instead of the periodic electric field described

above. (e.g. as discussed in reference to a chirped grating).

In one implementation of the just-described embodiment, a magnitude of the change in refractive index of material 131 is fixed, as a function of distance in the predetermined direction P. Such an implementation may be used to provide another kind of optical device, namely a chirped grating that reflects light of different wavelengths, for use in dispersion compensation. Specifically, the chirped grating applies a negative chirp which is opposite in sign to the chirp applied by an optical fiber through which the light incident in material 131 has passed, and has undergone dispersion.

Alternatively, a magnitude of the change in refractive index of the substance 131 due to the presence of an electric field is not fixed as described above, and instead changes with distance along the predetermined direction P. In such an embodiment, the instantaneous spatial frequency of the refractive index of material 131 remains constant.

Furthermore, in yet another alternative embodiment, the magnitude of the change in refractive index of substance 131 due to presence of the electric field, as well as an instantaneous spatial frequency of the refractive index, both change with the distance in the predetermined direction P.

A device in accordance with this invention includes an optical waveguide embedded in an electro-optic material that is exposed to a synthesized electric field of the type described above. Such a device may be used as an optical filter. The filter may be used in combination with a gain

block between two mirrors, to form an optically resonant cavity, for use as an extended cavity laser in one embodiment. Specifically, the filter can be used to produce a wavelength agile laser by changing the electric field that is being synthesized, for use in optical communications. Such a laser is particularly amenable to rapidly reconfigurable optical networks as well as to longer time constant reconfiguration such as wavelength sparing. Alternatively, in another embodiment, the filter is used directly to perform wavelength filtering in an optical add drop multiplexer or an optical switch. In yet another embodiment, the filter is used for dynamic power balancing or for dynamic gain equalization.

In one specific embodiment, an electric field synthesized by use of electrode structure 100 (FIG. 16) is periodic in space along the predetermined direction P, and is used to change the refractive index of waveguide 132, so that a period of the change in refractive index is linearly related to a wavelength in the range of 1300 nanometers to 1700 nanometers. Specifically, in one particular embodiment, the electric field has a period in space equal to N times half the wavelength that is linearly related. Wherein N is an integer greater than zero.

The just-described condition ensures that light of the wavelength that is linearly related is the light that is reflected, with a portion of the light being reflected each time the periods of the electric field and the light match. For example, if N is the integer 2, a portion of light is reflected at an interval along the direction P equal to a wavelength. Alternatively, if N is the integer 3, reflections occur at distances that are multiples of three

wavelengths. The relative distance between and electric field that is synthesized, and an electric field due to light may be changed as described above in reference to FIG. 10, for example, if there is an offset between the two electric fields.

Electrode structure 100 (FIG. 16) may be separated from waveguide 132 in the direction Z by a distance that is sufficiently small for waveguide 132 to exhibit a change in refractive index due to presence of the electric field synthesized by electrode structure 100. In one particular example, the distance between electrode structure 100 and waveguide 132 is five microns, so that the far field effects (that occur at distances similar to or greater that the pitch P of the electrode structure) are used in changing the refractive index of waveguide 132

In another example, the distance is only 2 microns, thereby to ensure that the refractive index change in waveguide 132 depends on the near field effect (that occurs at distances less than the pitch P), which is illustrated at the extremities of the electric field, as seen in circle C4 (FIG. 5). Depending on the embodiment, waveguide 132 may be at a distance effectively equal to a pitch p (FIG. 2A) between the electrodes E1-EN. In one example, the thickness T (FIG. 16) of the electro-optic material 131 (e.g. formed of lithium niobate) is 10 millimeters, and a buffer layer (see FIG. 21) has a thickness of 100 nanometers, and waveguide 132 is no more than 10 millimeters away from structure 100.

An optical waveguide 132 formed in the electro-optic material 131 should support substantially the lowest order spatial mode of the guide, so as to allow facile coupling of

the waveguide within the electro-optic material 131, to other single mode waveguides outside the electro-optic material 131. See, for example, the article entitled "End Fire Coupling Between Optical Fibers and Diffused Channel Waveguides", by Burns et al, Applied Optics, Vol. 16, No. 8, August 1977, pages 2048-2050 that is incorporated by reference herein in its entirely.

Although in one embodiment illustrated in FIG. 16 and described above, the synthesized electric field is used to change the refractive index of electro-optic material 131 sufficient for the light to be converted from a forward propagating mode to a backward propagating mode, such structures can also be used to convert light between any two modes of a multi-mode waveguide. Specifically, in an optical device 140 (FIG. 17), two waveguides 141 and 142 are located adjacent to one another, separated by a separation distance S. For example, if a fundamental mode supported by each of two identical waveguides has a majority of power in a width W than the distance between these two waveguides can be 2W and still be sufficient for an optical device containing the two waveguides to function effectively.

In this particular embodiment, each of electrodes E1-EN covers both waveguides 141 and 142 so that both waveguides 141 and 142 are subject to the same electric field. However, the electrodes could only overlap one of the waveguides and still be effective. In such an embodiment, light in the two waveguides has different propagation constants and application of a synthesized electric field as described above causes the propagation constant to phase match, and therefore the transfer over of energy. Such an optical device 140 may be used in an add-drop multiplexer in

a telecommunication network, to transfer a wavelength of light, e.g. from a first waveguide 141 to a second waveguide 142.

In the embodiment illustrated in FIG. 17, each of the two modes in the respective waveguides 141 and 142 propagates in the same predetermined direction P, although in an alternative embodiment, the directions of light in the two waveguides 141 and 142 are opposite to one another, e.g. the P direction and the -P direction. The relevant equations used to ensure coupling of energy between modes are given below as equations (5) and (6).

In yet another embodiment illustrated in FIG. 18, a device 150 has two electrode structures 151 and 152, with a first electrode structure 151 covering two waveguides 153 and 154, and the second electrode structure 152 covering two waveguides 154 and 155. A common waveguide 154 is present between the two electrode structures 151 and 152, so that a portion of light incident on waveguide 153 is transferred by common waveguide 154 to another waveguide 155. Device 150 implements a two stage filter that can provide twice as good performance as a single stage filter of the type illustrated in FIG. 17.

In still another embodiment, electrode structures 161 and 162 (FIG. 19) that are similar to the above-described structures 151 and 152 each cover three waveguides instead of just two. Specifically, structure 161 covers waveguides 163, 164 and 166, whereas electrode structure 162 covers waveguides 163, 164 and 165. In this embodiment, waveguides 164 and 163 are common to the two electrode structures 161 and 162. Waveguides 166 and 165 are not connected to one another, although they are present in a space between

waveguides 163 and 164. In one use of the device illustrated in FIG. 19, light of a particular wavelength in waveguide 166 is coupled over to both of waveguides 163 and 164 on application of a synthesized electric field by electrode structure 161 and this light is coupled over to waveguide 165 by application of an identical electric field by electrode structure 162, thereby to result in a four stage filter.

Although in the above-described embodiments a waveguide has been illustrated as being in a direction P that is parallel to the direction of the periodicity of an electric field synthesized by application of the different voltage levels to the electrodes, in other embodiments the two directions may be different from one another. Specifically, an angle θ between direction of a waveguide and the predetermined direction P of the electric field being synthesized, creates an appearance of a change in the period of the electrodes (assuming the electrodes are periodically spaced), so that the electrodes appear to be further apart as the distance increases in the predetermined direction P.

The change in the refractive index of a waveguide is dependent on the cos (θ) component of the electric field (i.e. the component in the direction of the waveguide). Depending on the physical principle being used, the conversion of energy may be between two forward propagation modes, as opposed to conversion of energy between opposite propagation modes, and for this reason design of the optical device may be different.

In yet another embodiment illustrated in FIGs. 20A-20C (of the type described above in reference to FIGs. 3-5 and 7-12), the synthesized electric field generated by use of an

electrode structure coupled to a set of voltage sources that are independently controllable is aperiodic instead of periodic. The aperiodic electric field of this embodiment is used for polarization mode conversion in a laser.

Specifically, light of one polarization mode is converted into light of another polarization mode by use of a substance 181 (FIG. 21) that is birefringent. Moreover, device 180 (FIG. 21) also includes a polarizer 182 formed by, e.g. a layer of metal that absorbs light of predetermined polarization mode, e.g. the polarization mode TM (or alternatively, polarization mode TE). Therefore, light in waveguide 183 that is not converted into the predetermined polarization gets absorbed, and light of the predetermined polarization is transmitted out.

Such a polarization mode converter can be used as a filter, because only light of a specific polarization mode is transmitted therethrough. Alternatively, instead of being transmitted out, such light can be reflected back by use of a reflector 252 (FIG. 22) for use of device 180 in a laser 200 (as described below in reference to FIG. 22). The light incident on device 180 may be of any polarization, e.g. TE or TM, as long as light of the same polarization is absorbed by polarizer 182, and an electric field synthesized by electrode structure 100 changes polarization of at least one wavelength of the incident light.

In one specific embodiment, the electric field generated by electrode structure 100 has a period in space in the predetermined direction P which is greater than or equal to four times the wavelength of light that is incident on waveguide 183, which is the light undergoing polarization mode conversion in waveguide 183, e.g. wavelength 1610

nanometers. Moreover, the periodicity of the synthesized electric field can be changed at any time by changing the voltage levels being applied to the individual electrodes.

In contrast, the prior art of U.S. Patent 3,877,782 discloses individual electrodes that cannot be independently controlled. Specifically, the selection of an oversampling factor F greater than 1 requires an electrode structure with a spatial pitch p greater than that appropriate for polarization mode coupling of a wavelength at λopt if alternating voltages must be applied to the electrode structure as taught by U.S. Patent 3,877,782. If one examines the prior art mentioned herein it may be seen that the implementation of oversampling of the electrode spatial period is absent. Additionally in the cited prior art the only applied voltage structure used is of alternating values.

As noted above, in one embodiment an electro-optic substance 181 that is present adjacent to the electrodes (FIG. 21), is birefringent, with a difference in refractive indexes in the two polarization modes of $|ne-no|=0.072$. The spatial period of 21 microns for the electric field corresponds to optimum polarization mode conversion at 1523 nm as illustrated in FIG. 3. Therefore, a variable polarization coupling process is combined with polarizing element 182 to produce optical attenuation for a particular polarization mode.

Once a cavity (FIG. 22) is formed by appropriate alignment of the optical elements, the wavelength (at which optimum coupling of optical power is achieved) is the resonator mode that sees the lowest loss. The mode coupled wavelength is therefore preferred over all others. Such

preference may also be described as differential loss. In many ways use of device 180 (FIG. 21) in the embodiment of FIG. 22 shares some similarity with an intra-cavity Lyot filter namely; the use of an optical element to alter the polarization eigenmodes of the laser resonator as a function of their wavelengths. Into this depolarized resonator a polarization dependent loss is introduced that modifies the loss structure of the polarization eigenmodes. As a result there is one resonator frequency at which the optical loss is the lowest.

A wavelength uncommitted Fabry-Perot gain chip 242 (FIG. 22) incorporating its own optical waveguide and excited by current injection is optically linked by optical coupler 246 (such as a fiber, a tapered waveguide, or a lens) to the waveguide 183 in the electro-optic substrate 181. The Fabry-Perot chip 242 exhibits polarization dependence in its optical gain and optical loss. An additional polarizing element may be inserted to complement the polarizing effect of the Fabry-Perot gain chip. On the extreme opposite facets of the lithium niobate chip 180 and the Fabry-Perot chip 242 cavity defining mirrors 252 and 243 are deposited.

The reflectivity of cavity defining mirrors 242 and 253 yield a sufficient cavity "Q" so as to allow laser oscillation to build up within the cavity. On the internal facets of the gain chip 242 and the electro-optic substrate chip 180 anti-reflective coatings 251 and 245 are deposited to eliminate the magnitude of any sub-cavity resonances. In addition, the optical coupler 246 is similarly coated with anti-reflective layers 247 and 248 and for the same reason.

Added to the electro-optic gain chip 180 is an electrode structure (e.g. formed of electrodes 253A-253N laid out substantially transversely to the device resonator axis. Prior to the deposition of these conductive electrodes 253A-253N, a buffer layer 134 formed of an optically transparent material may be deposited, to lower the propagation losses in the electro-optic waveguide 183. Each of the aforementioned electrodes 253A-253N are independently controlled. The spatial period of the electrodes 253A-253N is such that they satisfy the following relationship

$$\Lambda = \lambda_{opt} \left(2F \left|n_e - n_0\right|\right)^{-1} \qquad (3)$$

where

Λ = Electrode period in space.

λ_{opt} = Wavelength at which the polarization mode coupling process is at its most efficient.

n_e = Refractive index of the electro-optic material in the extraordinary axis.

n_o = Refractive index of the electro-optic material in the ordinary axis.

F = Oversampling factor (>1).

In laser 200 (FIG. 22), a thermoelectric cooler 239 is interfaced with a heatsink 240 and a device submount 241. A semiconductor gain chip 242 is affixed to the submount 241.

Submount 241 is designed to have various surfaces used to mount one or more components used to implement a device, such as a laser. For example, submount 241 may have surfaces at heights H1, H2 and H3 (FIG. 22) that are chosen to ensure that light from a component (e.g. chip 242) reaches another component (e.g. chip 181) and vice versa. Depending on the manufacturer, in one example, H3-H1 is 1 mm and H2-H1 is 0.5 mm.

As noted above, the semiconductor gain chip 242 has a cavity defining mirror 243 placed on its outermost surface, and also has a contact pad 244 for the injection of a current Idiode, and also has an anti-reflecting surface 245 placed on the intra-cavity surface of the gain chip. The output beam from the gain chip 242 is interfaced with a coupling optic 246 that has anti-reflective surfaces 247 and 248 deposited on all its intra-cavity interfaces. Surfaces 291 and 292 are heating and cooling surfaces of the cooler 239 and are normally made of ceramic.

Coupling optic 246 ensures power coupling efficiency between a waveguide (not shown) in gain element 242 and another waveguide 249 in electro-optic chip 180. The waveguide chip 180 has an anti-reflective surface 251 on its intra-cavity face and the remaining cavity defining mirror 252 is deposited on the outermost face of the electro-optic chip 180. Overlaid upon the upper surface of the electro-optic chip 180 is a buffer layer 134 consisting of an optically non-absorbing material such as silica. The buffer layer 134 covers the entire length upon which electrodes 253 are to be overlaid.

The electrodes are electrically connected by contacts 254A-254N to an array of sources 255 of voltages VA-VN, to

introduce polarization dependent loss in a direction at normal incidence to the horizontal surface 181H of the electro-optic chip 180. An overlap between the electric field environment 256 and the transverse dimensions of waveguide 183 is required to ensure that the refractive index of the waveguide 183 changes in response to the electric field, and such an overlap is shown in FIG. 22.

In one embodiment, the analog voltages VA-VN, wherein A $\leq$ I $\leq$ N are determined according to the following relation

$$VI=A*\cos(2*\pi*\Lambda*|n_e-n_o|*I/\lambda_{opt,des}) \quad (4)$$

Where

A = Amplitude constant, determined as described below.

π = The fundamental constant pi.

Λ = Electrode period.

$\lambda_{opt,des}$ = Wavelength at which the polarization mode coupling process is desired to be its most efficient.

n_e = Refractive index of the electro-optic material in the extraordinary axis.

n_o = Refractive index of the electro-optic material in the ordinary axis.

I = Electrode number.

In practice, the effective birefringence |ne-no| are weakly dependent on wavelength of the synthesized electric field and on waveguide properties, thus in an experimental setting, the designer will have to experimentally perturb

$\lambda_{opt,des}$ in order to obtain most efficient mode conversion at precisely the desired wavelength.

Consider the wavelength $\lambda_{opt,des}$ at which the most efficient mode conversion is effected. The fraction of energy that is converted from one mode of propagation to the other mode of propagation is a function of the amplitude constant A, the guide properties, the overlap between the electric field due to the fixed electrodes and the electromagnetic field of the light, and the total length of the mode converter section (nominally the product of the total number of electrodes and the electrode period L). In a practical experimental setting, some tuning will be required to maximize the energy conversion from one mode to the other.

The relevant equations needed to determine the coupling of energy between modes (in either the same waveguide or in adjacent waveguides) is given by

$$\frac{dM}{dz} ik_{MN}(Z)Ne^{-i(\beta M-\beta N)z} \qquad (5)$$

$$k_{MN} = \frac{\beta_N}{4}\int_{-\infty}^{\infty}\frac{\varepsilon^2}{\varepsilon(x)\varepsilon_0} r(x,z)E^{(0)}(x,z)H_{y,M}(x)E_{y,N}(x)dx \qquad (6)$$

Where

M = the (complex) amplitude of the waveform in mode M

N = the (complex) amplitude of the waveform in mode N

z = the distance traveled down the guide

β_M = the propagation constant of mode M

β_N = the propagation constant of mode N

ε = permittivity of the waveguide material(s)

ε_0 = permittivity of free space

r = the electro-optic tensor of the waveguide material(s)

$E^{(0)}$ = the electric field due to the electrodes

$H_{y,M}$ = y component of the magnetic field of M mode

$E_{y,N}$ = y component of the electric field of N mode

Since $E^{(0)} = -\nabla V$, the electric field can be computed from the gradient of the electric potential in waveguide's material. The total electric field in the material can be computed from the electrode voltages using finite difference methods. Since the scaling of A will effect the scaling of the electric field E(0), larger A produces more rapid coupling as the light travels down the waveguide. "A" is chosen so that complete coupling occurs as the light exits the mode conversion section of the waveguide (which is the section having electrodes 253A-253N). In practice, selection of A is determined experimentally.

In one particular example of such a device, the mode converter is 5.12 mm long, the polarizer is 2 mm long and the device includes a spare length of 0.08 mm. The elctrodes have 10 micron pitch, and are 200 microns long and each electrode has 5 micron width, and there are 512 electrodes. The buffer layer is 180 nanometers thick and

waveguide is 7 microns wide (and alternatively 9 microns wide). In this example "A" is 16 volts. The spare length may be used, for example, to align the electric field being synthesized with the electric field of the light travelling in the waveguide as discussed above in reference to FIG. 10.

Voltages VA-VN (FIG. 22) that are applied to electrodes 253A-253N are determined by a designer as follows. The designer initially selects a transfer function in the digital domain that models the electric field to be generated to perform a specific mode conversion that is desired in the device being designed. Thereafter, the designer uses the transfer function in a computer to obtain the digital values of voltage levels that are to be applied to the electrodes (based on the pitch p). The transfer function may be used as described by the software in Appendix A, provided as MATLAB files "pfe.m", "pfe-help.m" that create a mathematical model of the electric field, and file "pfilt.m" which uses a linear program and the mathematical model to determine a set voltage levels for 1550 nm wavelength light and 10 micron pitch of electrodes, and 101 total electrodes. MATLAB software is available from The Mathworks, Inc. of Massachusettes. .

Next, the designer simulates the electric field that will be synthesized if the voltage levels were to be applied to the electrode structure. The simulated electric field merely approximates the transfer function initially chosen by the designer, due to the fact that the electrodes are limited to N in number and are separated from one another by a pitch p. The designer then uses the simulated electric field to determine whether a desired optical effect is being

achieved and if not, selects a different transfer function and repeats the above-described process.

Depending on the need, the designer may optimize the above-described process by use of, for example, linear programming, 2nd order cone programming, semi-definite programming (using linear matrix inequalities) and non-linear programming. One example of linear programming is attached hereto in file "pfilt.m" in Appendix A. Such linear programming is described in, for example, an article entitled "FIR Filter Design Via Spectral Factorization And Convex Optimization" by Shao-Po Wu, Stephen Boyd and Lieven Vandenberghe that is incorporated by reference herein in its entirety.

The attached files of Appendix A generate the graphs illustrated in Figs. 20A-20E. Voltages VA-VN (FIG. 22) that are applied to electrodes 253A-253N are controlled in one embodiment by a digital computer 302 (FIG. 23) that is coupled to multiple voltage sources 301, each of which may be implemented by one of digital to analog converters (DACs) 301A-301N, as illustrated in FIG. 23. Each DAC 301A-301N in turn is connected to a single electrode (not shown in FIG. 23; see FIG. 22). In this embodiment, DACs 301A-301N are all connected to an address bus and a data bus, which is in turn connected to the controlling digital computer 302.

Computer 302 of this embodiment is also coupled to thermoelectric cooler 239 (described above) via a power regulator to control the supply of power to cooler 239, and is further coupled to receive a temperature signal from a thermistor 261 via an analog to digital converter (ADC). Thermistor 261 is physically attached to waveguide chip 180 to provide a measure of the temperature of waveguide chip

180. Therefore, computer 302 controls the temperature of waveguide chip 180 via a feedback loop, in the normal manner (e.g. in the well known "proportional integral" manner).

The attached files of Appendix A generate the graphs illustrated in Figs. 20A-20E. Specifically, a transfer function encoded in the file "pfilt.m" defines matrices and vectors "A," "B," and "F" and is used to generate an electric field for pass band gain of 1 and stop band gain of 0.9 or less, with optimization to make the pass band as narrow as possible subject to voltage levels being in the range -100 volt to +100 volt. In the file "pfilt.m", the optimization variable is "xtemp" and the computer is programmed to minimize F^T (xtemp) subject to A*xtemp < B and VLB < xtemp <VUB wherein VLB and VUB are respectively -100 and +100. Such optimization minimizes the pass band width to 500 GHz for a 1550 mm laser (in the band 1520-1620 nm.)

Computer 302 of this embodiment is further coupled to diode driver 244 (described above) via a DAC to control the supply of current to gain chip 242, and is further coupled to receive signals from a wave locker and power monitor 262 via an analog to digital converter (ADC) 263. Wave locker and power monitor 262 provides an indication of the power of a laser signal being generated by device 200. Wave locker and power monitor 262 may include, for example, two diodes. In one implementation, the two diodes generate sum and difference signals of the energy incident thereon and these two signals are transmitted on a two-wire bus to the ADC. In an alternative implementation, one diode is used for measuring the wavelength of the laser beam being generated, and another diode is used for measuring the power being generated. Therefore, computer 302 controls the wavelength

and power of the laser beam generated by waveguide chip 180 via a feedback loop.

The analog voltages applied to electrodes 253A-253N are set by a computer program that performs the method 350 of FIG. 24 (described below). Specifically, in one embodiment, computer 302 hunts for the best set of voltage levels to be applied from among a group of sets that are predetermined and stored in memory. For example, a single set of voltage levels VA-VN (also called "tuning point") may be effective at a specific temperature to produce a laser of a specific wavelength. If the temperature changes, a different set of voltage levels is needed. For this reason, computer 302 starts with a set SC (see act 351 in FIG. 24) that is known (from experiment) to produce a laser of the specified wavelength λs. Thereafter, computer 302 repeated performs acts 352-355 in a loop as follows.

In act 352, computer 302 reads values of the wavelength and power from ADC 263 (described above). Thereafter, in act 353, computer 302 replaces the set SC of voltage levels that are currently applied with another set SN that is known to produce a laser of the next larger wavelength λn (depending on the resolution, such a wavelength may be just 0.01 nm larger than the current wavelength). Then computer 302 again reads from ADC 263 the values of wavelength and power generated by use of set SN.

Then in act 354, computer 302 replaces set SN with another set SP that is known to produce a laser of a next smaller wavelength λp, and again reads from ADC 263. Next, in act 354 computer 302 determines which of the respective sets produced the best readings (e.g. which produced the most power at the specified wavelength λs), and then selects

this set as the current set for the next iteration of the loop (and returns to act 352, e.g. after waiting for a predetermined duration). In this manner, over time, a single set SC is used (for successive periods of the predetermined duration), as long as the operating conditions remain unchanged.

Devices that include electrodes that are insulated from one another and that carry independently controllable voltages may be packaged in any manner well known in the art. Moreover, such devices can be packaged with any components well known in the art. In one example, a mode converter has a number of electrodes of the type described above, and is packaged with a laser diode and a submount thereby to form a laser. Instead of or in addition to the laser diode, a gain medium and an optical coupler may be enclosed in the same package that encloses a mode converter. For example, in one implementation, items 301, 102, 263-267, 239, 180, and 261 of FIG. 23 are all packaged together. In such an implementation, a power monitor may also be included in the same package with a wave locker external to the package.

Numerous modifications and adaptations of the embodiments described herein will be apparent to the skilled artisan in view of the disclosure. For example, although device 200 illustrated in FIG. 22 is a laser, a similar device 400 (FIG. 25) can be constructed without mirror 252, for use as a filter.

Furthermore, instead of using a buffered DAC for each electrode as illustrated in FIG. 23, a doubly buffered DAC may be used as illustrated in FIG. 26, e.g. so that a new set SN is present in the DACs and is available for use while

a current set SC is being currently applied to the electrodes. Moreover, instead of a doubly buffered DAC, a combination of a read-only-memory and a DAC may be coupled to each electrode as illustrated in FIG. 27.

Also, instead of using multiple DACs one for each electrode, a single DAC may be used for all electrodes if each electrode is coupled to the single DAC through an individual analog sample and hold circuit, as illustraetd in FIG. 28. Specifically, this embodiment utilizes an analog bus with a single wire going to each sample and hold from the DAC (i.e. the inputs to all the analog sample and hold circuits are all connected to the output of a single DAC). The DAC is connected to a digital computer. In order for the digital computer to assign a voltage to an electrode, the DAC is commanded to the desired electrode, and the sample and hold associated with the electrode is taken to the sample state, and then returned to the hold state. The process is in turn repeated with each electrode. Furthermore, as illustrated in FIG. 29, each electrode could be coupled to the DAC through a pair of sample and hold circuits, wherein one circuit holds the voltage level being currently applied and another circuit holds the voltage level that is to be applied next.

As another example, orientation of device 180 can be upside down relative to the arrangement illustrated in Fig. 22 (i.e. electrodes 253A-253N are sandwiched between device 180 and submount 241).

The foregoing has outlined rather broadly the more pertinent and important features of the present invention. It should be appreciated by those skilled in the art that the embodiment 3 described herein may be readily utilized as

a basis for modifying or designing other arrangements and methods for carrying out the present invention. It should also be realized by those skilled in the art that such equivalent constructions, devices and methods do not depart from the spirit and scope of the appended claims.